

PEGMATITE VEINS AND THE SURROUNDING ROCKS

III. Structural control of small pegmatites in amphibolite, Rytterholmen, Kragerøfjord, Norway

BY
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A b s t r a c t: A study was made of the structural position of 266 small, tabularly shaped pegmatites in an amphibolite in the pre-Cambrian Kongsberg—Bamble formation on the island Rytterholmen near Kragerø, southern Norway.

The pegmatites and the surrounding amphibolite are briefly described petrographically. Special attention is paid to the analysis of the structural position of the pegmatites in terms of shear-stress zones and tension directions which developed during the dynamo-thermal metamorphism of the area. The long axes of the pegmatites show a pronounced directional orientation in each of the five small areas examined in detail. This preferred orientation is related to zones of shear which are about perpendicular to the tension directions. The ratio length/width of the pegmatites is found to be roughly inversely correlated to the basicity of the surrounding amphibolite. The theory of origin by metamorphic differentiation is discussed and found to be the most satisfactory explanation of the genesis of the pegmatites. Basified zones in the amphibolite adjacent to the pegmatites and the difference between the An % in the surrounding amphibolite and the pegmatites substantiate this conclusion.

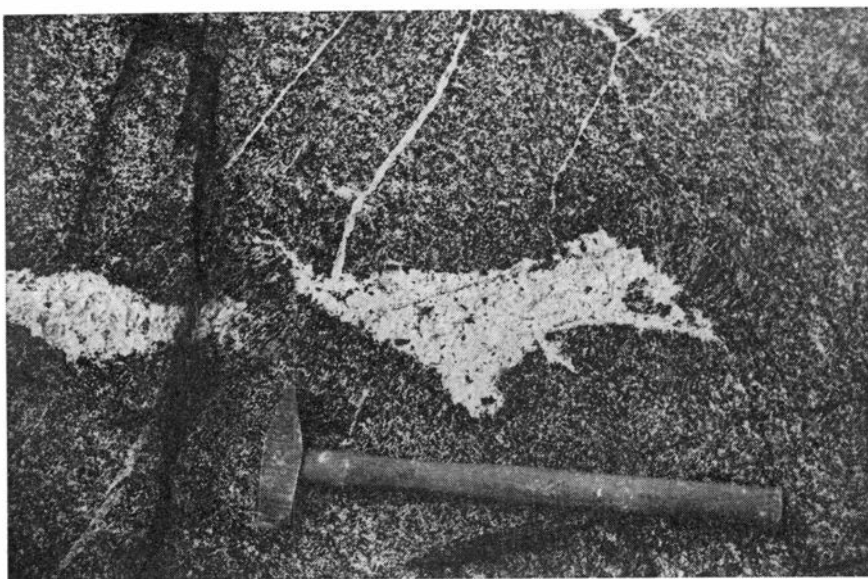


Fig. 1. Shows long, thin, conformable pegmatites (type 1) amputated by pegmatite body (type 3). Hammer is 48 $\frac{1}{2}$ cm long. Photo at area A by P. Reitan.

Introduction

This paper is primarily a study of a particular type of small pegmatite veins found in the amphibolite exposed on the island Rytterholmen, located about 6 km almost due east of the town of Kragerø on the south coast of Norway.

Knowledge of the general geology and of special areas and characteristics of the Kragerø district are to be found in the works of BRØGGER (4, 5), J. A. W. BUGGE (6), GREEN (8), HOFSETH (9), and HOLTEDAHL (10). Especially useful for the area near Rytterholmen is the map by BRØGGER (5).

Rytterholmen consists primarily of a gneissic amphibolite, which in zones is rather garnet (almandine-pyrope) rich, and a micaceous quartzite. The rocks have been thoroughly metamorphosed in the amphibolite facies, as indicated by the petrographic descriptions of the amphibolite on Rytterholmen (p. 178) and the descriptions of the petrography of the near-by islands by BRØGGER (5) and HOFSETH (9).

On Rytterholmen there are four different types of pegmatites in the amphibolite. The oldest pegmatite veins, type 1, which are cross-

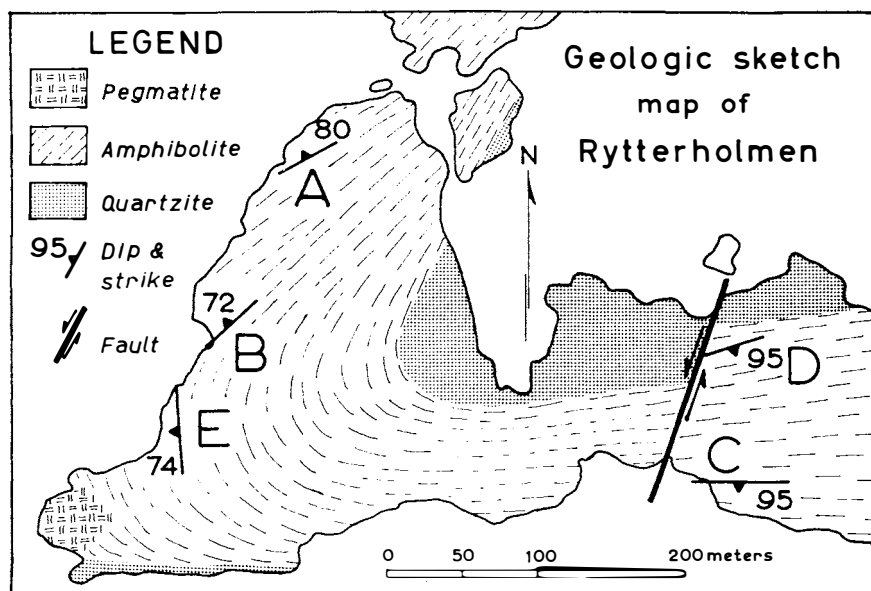


Fig. 2.

cut by all of the others, are thin, long, primarily plagioclase pegmatites which are conformable to the gneissic structure of the amphibolite (fig. 1). Two types were probably formed approximately contemporaneously: type 2 is an individual, massive, irregular pegmatite, found at the apex of the main anticline on Rytterholmen; type 3 consists of numerous, small pegmatites of sometimes slightly irregular, always elongate shape (tabular or pillow shaped in three dimensions). These have been the object of primary interest in this study. The youngest veins, type 4, which by virtue of their grain-size may be called pegmatites, are long, thin, crack-fillings composed either of quartz and a little calcite or calcite and dolomite. These veins cross-cut all other structures and are clearly the youngest; they are probably a very late feature of the history of the area.

Petrography

Five small areas (fig. 2) of perfectly exposed rock were found on Rytterholmen. From these areas samples of the pegmatites of type 3 and the amphibolite were taken.

PEGMATITES

The pegmatites consist primarily of white plagioclase (sometimes with a very faint greenish tinge) and clear quartz, the former being predominant, with some biotite, occasionally a little hornblende, and rarely a little garnet. Garnet is present only in those zones where the amphibolite is garnet bearing.

The grain-size of the plagioclase and quartz is up to 2 cm in largest dimension, more normally nearer 1 cm. Biotite occurs in flakes up to 1 cm across, though generally near $\frac{1}{2}$ cm. Hornblende and garnet, when present, are slightly finer-grained.

The composition of the plagioclase is quite constant; the most calcic plagioclase is An₄₀ and the least calcic is An₃₈ (table 1 and fig. 3).

Table 1

Composition of plagioclase in pegmatites¹

Area	A	B	C	D	E
An % in plagioclase	38	38	40	39	38—39

¹ Determined by the refractive indices of cleavage flakes for the two orientations (001) and (010), the method of Tsuboi, and by the extinction angle in the plane $\perp$ (001) and (010) and the maximum extinction angle in the zone $\parallel$ (010) using the universal stage.

AMPHIBOLITE

The amphibolite is mostly homogeneous, dark, medium-grained and shows reticular (network) fabric perpendicular to the linear structure. The essential minerals are hornblende and plagioclase; the most abundant mineral is always hornblende.

Hornblende occurs in rather elongate, idioblastic grains with ragged terminations, the orientation of which is responsible for the gneissic, linear structure of the rock. Hornblende shows pleochroism α = light olive-green, β = olive-green, and γ = dark green; absorption scheme $\gamma > \beta > \alpha$.

Plagioclase always constitutes more than 20 % of the rock. Its shape is irregular. It is usually slightly sericitized. At three of the areas from which samples were taken the composition of the plagioclase is An₄₂; at two areas the composition is An₄₄ (table 2 and fig. 3). Albite and pericline twinning are very common.

Table 2
Modal analyses of thin-sections

Sample no.	Plagioclase			Hornblende	Quartz	Biotite	Opaque	Apatite	Zircon	Chlorite	Epidote	Calcite	Σ Dark ²
	An ¹	Total	Albite	Anorthite									
9A-RC1	44	20.8	11.7	9.1	62.5	6.9	7.1	1.5	* ³	*	0.3	— ⁴	70.5
9A-RE1	42	23.2	13.6	9.6	56.1	5.9	1.4	0.3	—	3.9	0.4	1.1	69.1
9A-RA1	42	27.8	16.1	11.7	57.8	8.7	3.7	0.3	*	0.4	—	0.3	62.9
9A-RD1	44	33.2	18.6	14.6	46.6	9.0	1.9	0.7	*	0.9	0.7	0.2	56.2
9A-RB1	42	40.6	23.6	17.0	48.2	6.3	2.4	0.3	*	*	—	—	52.8

¹ An content of the plagioclase determined by the extinction angle in the plane (001) and (010) and the maximum extinction angle in the zone (110) using the universal stage.

² The sum of hornblende, biotite, opaques, and chlorite (secondary after hornblende).

³ The asterisk indicates that the mineral is present but in amounts less than 0.2 %.

⁴ The dash indicates that the mineral was not observed in the thin-section.

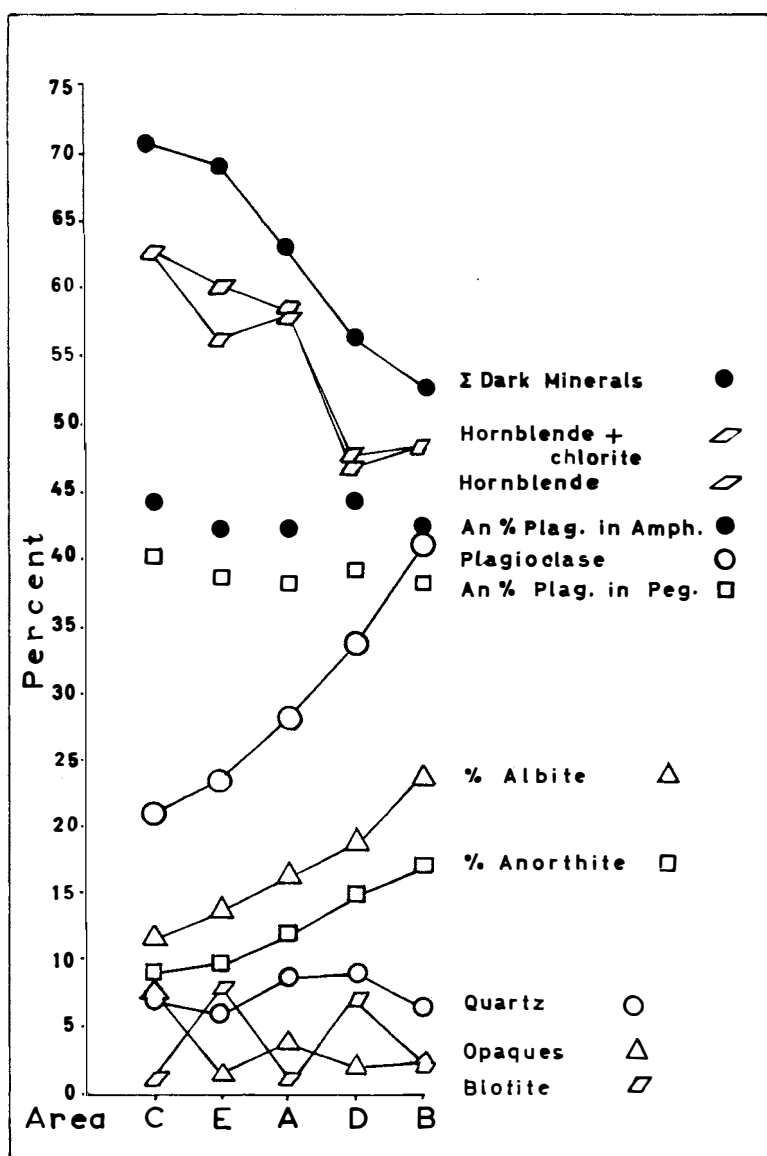


Fig. 3. Results of modal analyses. Total plagioclase is also separated into anorthite and albite. Anorthite percent in plagioclase from amphibolite and from pegmatites of type 3 shown by solid circles and open squares, respectively, unconnected by lines.

The accessory minerals always present are quartz, biotite, apatite, and opaques (pyrite, magnetite, and hematite). Zircon, epidote, penguin (secondary, primarily after hornblende), and calcite are frequently present and limonite is very rare.

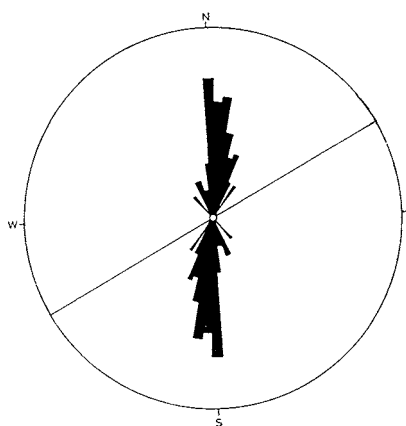
Modal analyses of a typical sample of the amphibolite from each of the five areas were made; the results are shown in table 2 and fig. 3.

Structure

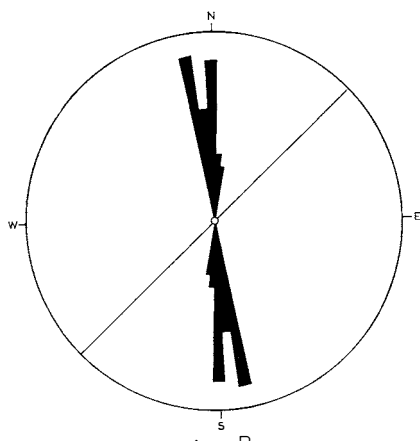
The primary structure on Rytterholmen is an anticline, the axis of which strikes N60E and plunges at about 75° towards the SW. The axial plane dips very steeply towards the NW. The southern limb of the fold strikes N90—100E and dips 95° S and the northern limb strikes about N50E and dips 80° N (see map, fig. 2).

Table 3
Orientation of the pegmatites at the five areas

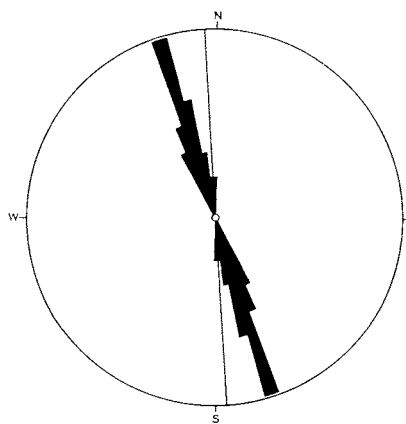
Direction	Percent of the measurements				
	A	B	C	D	E
N 62½—68½ W.....				9	
57½—62½				21	
52½—57½				25	
47½—52½				15	
42½—47½	1		5	9	
37½—42½	0		19	6	
32½—37½	0		9	6	
27½—32½	0		29	9	7
22½—27½	2		5		13
17½—22½	2		19		48
12½—17½	1		14		20
7½—12½	1	38			7
2½—7½	4	17			2½
N 2½ W—N 2½ E.....	26	35			2½
N 2½—7½ E	18	6			
7½—12½	20	4			
12½—17½	10				
17½—22½	5				
22½—27½	6				
27½—32½	2				
32½—37½	0				
37½—42½	2				
Number of meas'm'ts. . .	85	52	21	33	75



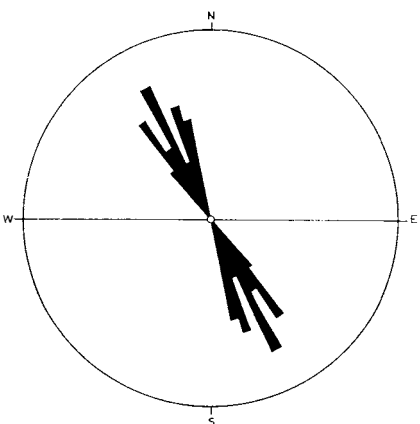
Area A
Fig. 4.



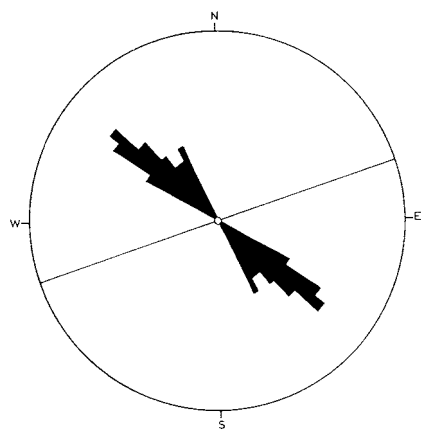
Area B
Fig. 5.



Area E
Fig. 6.



Area C
Fig. 7.



Area D
Fig. 8.

Fig. 4—8. Orientation of the long axes of the pegmatite bodies at areas A, B, E, C, and D. The area blackened within each 5° segment of the circle is proportional to the percentage of measurements within that segment. The outer circle is at 49 %. The local strike is represented by the diameter drawn.



Fig. 9. Pegmatites of type 3 with change of strike of amphibolite and basified zones adjacent to them. The match box is 5 1/2 cm long. Photo at area A by P. Reitan.

Within the amphibolite there are many small, elongate pegmatites. The strike direction of 266 of these distributed over the five selected areas was measured. It was possible to measure the dip of only about 25 % of these tabular or pillow shaped bodies. In all cases the dip was quite steep, varying between about 80° and 95°. Measurements were confined to virtually horizontal rock surfaces and therefore all of the measurements of the strike of the long axes of the pegmatites are used, even when the dip of the pegmatite was unobtainable. The results of these measurements are presented in table 3 and graphically in figs. 4 to 8.¹

In these figures it can be seen that within each of the five areas there is a very pronounced preferred orientation of the long axes of

¹ In these figures the blackened area, not the length, within each 5° segment of the circle is proportional to the percentage of measurements which fell within that segment. Thus the first percent is accorded greater length than any thereafter, the length per percent diminishing as the width of the segment increases. The radius of the outer circle equals the length to which any 5° segment would be blackened if 49 % of the measurements fell within it. The solid line transecting the circle represents the direction of the strike of the amphibolite.

the pegmatite bodies, though this direction is not the same in these areas nor is the angle between this direction and the strike of the amphibolite constant.

The amphibolite is very clearly gneissic at areas A, C, and D, a little less strongly so at area B, and nearest the apex of the fold at area E the gneissic structure is discernable though with some difficulty. Near the pegmatite bodies there can be seen a change in the direction of the strike of the amphibolite (figs. 1, 9, and 10).

Genesis of the pegmatites

Only the pegmatites designated type 3 (p. 000) have been the object of special attention and therefore only the genesis of these pegmatites will be discussed in detail here. Of the others suffice it to note that the oldest pegmatites, those of type 1, occur as long, thin veins parallel to the strike, a structural position which corresponds to that along which one would expect concentric shear-planes due to elastic stress in an elastically folded layer (DE SITTER, 7, p. 74); type 2 occurs as a massive, irregular body at the apex of a fold, a site at which maximum tension and minimum pressure would be expected to prevail; and those of type 4 occur as fillings of apparently very late joints — also low pressure volumes.

The significance of the preferred orientations of the pegmatites of type 3 may not at first seem immediately self-evident and it is therefore intended to analyze the structural conditions which prevailed at the five areas in terms of tension and shear. The reader is asked to keep in mind that the pegmatites occur in an amphibolite band 150 m and more thick which is surrounded by a micaceous quartzite, and that the whole area was under the P, T conditions of the amphibolite facies during the dynamo-thermal metamorphism of the area. Such being the case the quartzite must be assumed to have been relatively plastic with respect to the amphibolite during deformation. Also, the pressure which caused the folding in the region concerned will be assumed to have been essentially perpendicular to the strike of the axial plane of the anticline revealed on Rytterholmen.

ANDERSEN (1 and 2) considered that the explanation to the openings in which new material crystallized, whether as perthite veins or as pegmatites in heterogeneous associations of minerals or rock

bodies respectively, might be found in the unequal thermal contraction of the containing body as opposed to its surroundings. He also admitted as a serious possibility, and as often probable, that the openings might have been caused by the stresses set up by orogenic forces in zones of intensive folding. He did not advocate the latter because «... the meager data now available on the elastic properties of rocks do not give any definite proof of it.» (2, p. 49). It is intended here, in the light of present knowledge, to investigate the validity of the second possibility.

Area A is located on the northern limb of the fold. The regional pressure is not far from perpendicular to the boundaries of the amphibolite here and one would therefore expect two oblique shear directions to tend to develop, these forming acute angles with the boundaries of the band; the exact size of these angles would depend on the physical properties of the amphibolite. Area A is, however, much closer to the axis of the anticline revealed on Rytterholmen than to the next syncline (cf. BRØGGER's map, 5), and one may therefore expect rotational shear (cf. DE SITTER, 7, fig. 72, p. 100) which would in turn result in a tensional direction oblique to the strike of the amphibolite and directed towards the core of the anticline. The shearing between the amphibolite and the quartzite at the contacts and (what results in the same thing) the plastic flow of the quartzite will subject the amphibolite to a shear couple which will cause a tensional direction in the amphibolite — this also oblique to the strike of the amphibolite and directed towards the core of the anticline. Still one more direction of shear may be anticipated in a relatively competent layer surrounded by less competent layers as the folding begins to approach isoclinal folding. This shear direction is approximately parallel to the direction of regional pressure (fig. 11) and will be strongest at points furthest removed from the axes of the folds, i.e., where the limb of the fold strikes most directly across the direction of regional pressure.¹ One additional direction of tension is also to be expected, it is parallel to the strike — the direction of stretching as the layer is folded — tending to induce tension joints across the layer. This tendency is enhanced by the plastic flow of the surrounding quartzite. Tension due to stretching of the folded layer will be

¹ This says nothing more than that the limbs of a competent layer will more likely be sheared across than will the arches of the folds.

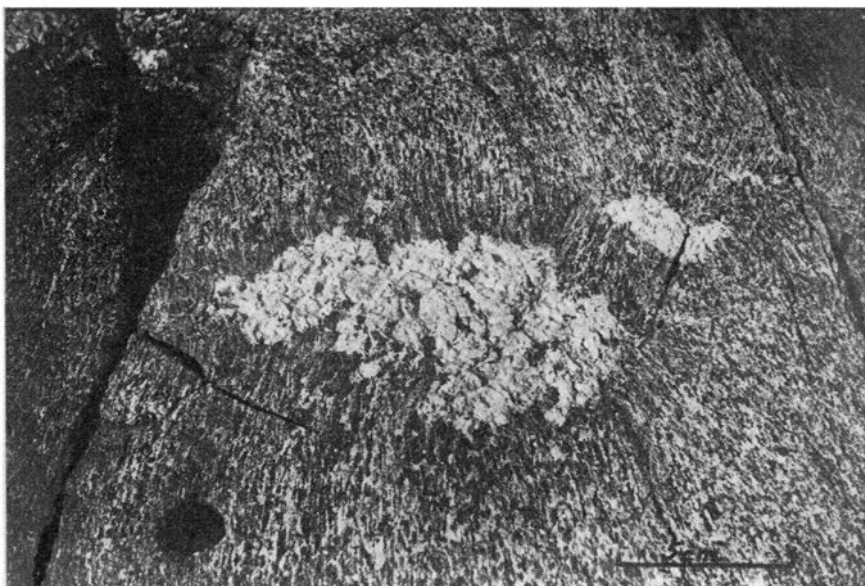


Fig. 10. Pegmatites of type 3. Note change of strike of amphibolite and basified zones adjacent to the pegmatites. Larger pegmatite is 12 cm long. Photo at area A by O. Christie.

greatest at the apex of the fold and on flanks at the points farthest removed from the apices; due to the plastic flow of the quartzite it will be greatest at the points farthest removed from the apices of the folds. These shear and tension directions are shown in fig. 12.

The direction of the preferred orientation of the long axes of the pegmatites at area A corresponds to these shear and tension directions as follows. Of the two oblique shear directions due to compression, one is near parallel to the long axes of the pegmatites. The direction of the tension resulting from the rotational shear is near perpendicular to the long axes of the pegmatites. The direction of the tension due to the shear couple resulting from the movement of the surrounding quartzite layers with respect to the amphibolite is also near perpendicular to the long axes of the pegmatites. The direction of the shear across the limbs of a competent layer approaching isoclinal folding is close to parallel to the regional pressure which itself forms a small angle with the direction of the long axes of the pegmatites, i.e., this shear direction is sub-parallel to the long axes of the pegmatites.

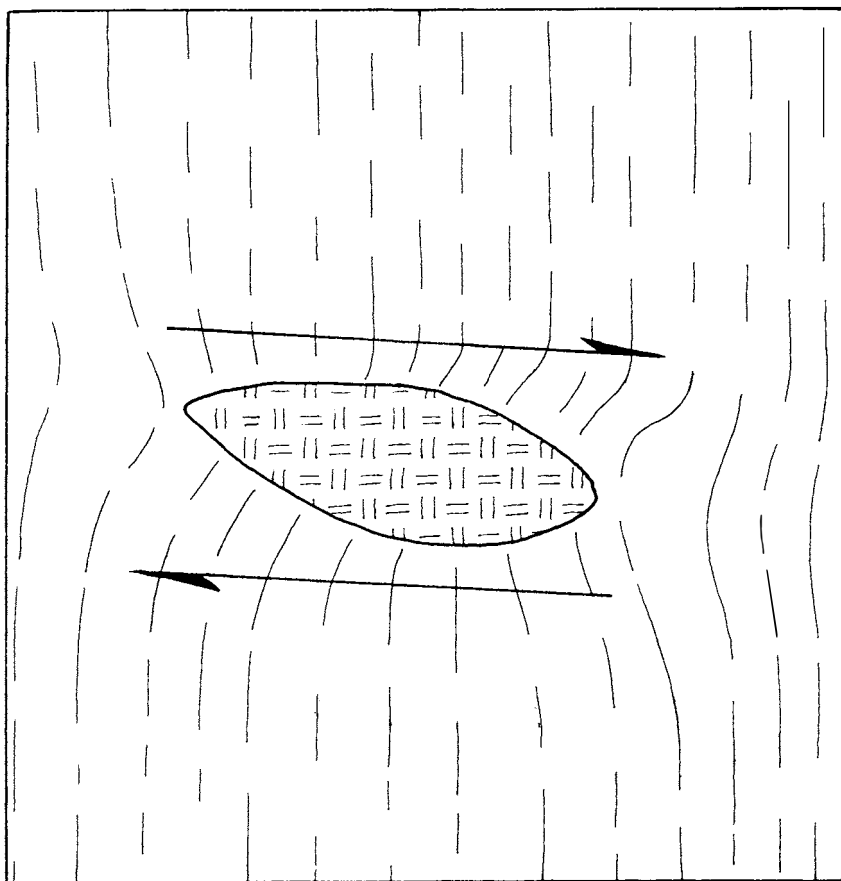


Fig. 11. Simplified and slightly schematized sketch from photo, fig. 10, showing the deduced shear couple parallel to the regional pressure. The gneissic structure indicates this shear plus some plastic deformation of the amphibolite.

Tension in the limbs of the fold due to stretching and due to the plastic flow of the quartzite will be approximately parallel to the strike of the amphibolite and therefore not far from perpendicular to the long axes of the cross-cutting pegmatites. There were therefore forces active tending to shear the amphibolite about parallel to the direction of the long axes of the pegmatites and tending to apply tension about perpendicular to this direction. This means that in the zones now occupied by the pegmatites the original minerals were subjected to a stress due to the shear and that these zones were low

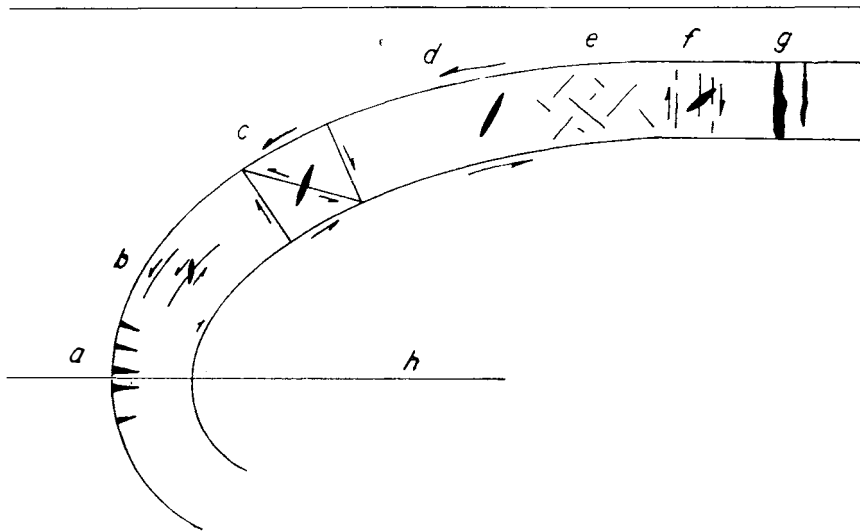


Fig. 12. Shear and tension directions summarized. The arrows show the relative directions of movement. Tension direction is across the black wedges, ellipses, and irregular cracks. a, tension joints; b, concentric shear joints; c, rotational shear; d, shear couple due to relative movement of surrounding layers; e, oblique shear due to compression; f, shear across the competent layer due to regional pressure; g, tension joints due to stretching and to plastic flow of surrounding layers; h, axial plane. Mostly after DE SITTER (7, fig. 72, p. 100).

pressure volumes due to the tension perpendicular to the long boundaries of the zones.

It is well known that crystals which are subjected to a shear-stress have greater chemical activity and tendency to decompose (and crystallize again in more favourable locations or orientations, i.e., recrystallize) than those which are not strained (BARTH, 3, p. 297, 304, MAC DONALD, 11, and RAMBERG, 12, p. 109). In low pressure zones it is also clear that minerals of large mol volume will be formed in preference to minerals of small mol volume, i.e., the relative stabilities of the minerals will be such that those of large mol volume will be favored (see e.g. the discussion in REITAN, 16, p. 302–303).

The pegmatites under consideration are small tabular or pillow shaped bodies. They are completely ductless. Therefore, for the reasons stated by REITAN (15, p. 228–232), magmatic and hydrothermal modes of origin for these pegmatites are excluded as quite unsatisfactory (see also SVERDRUP, 17).

The pegmatites are parallel to directions of shear and the direc-

tions of low pressure zones to be expected. It is therefore proposed that these pegmatites formed by a process of metamorphic differentiation which was initiated and controlled by the structural conditions which prevailed. In the zones in which the pegmatites grew the activity of the original minerals was increased by the shear-stress and recrystallization began. Because these same zones were at the same time low pressure zones, the stability of minerals of large mol volume was relatively increased. Concentration gradients were thereby initiated such that material from the diffuse phase in the adjacent rock migrated to the low pressure zones and there crystallized, this material being the constituents of the relatively most stable minerals in the low pressure volumes, i.e., primarily plagioclase and quartz. Of course the composition of the minerals which crystallized in the low pressure volume was dependent on the composition of the environment. K-feldspar, for example, could not grow in the pegmatites, even though the mol volume of K-feldspar is favourably large, because not enough K could be provided to the phase from which the minerals of the pegmatites crystallized by the K-poor amphibolite. As the diffuse phase in the adjacent amphibolite was depleted, material moving down the concentration gradient towards the volume in which the pegmatite grew, minerals in the amphibolite (namely primarily plagioclase and quartz) simultaneously decomposed in order to maintain equilibrium between the solid and the diffuse phases. This process results in a leaching of the adjacent amphibolite of the minerals enriched in the pegmatite, i.e., the light colored minerals plagioclase and quartz. Such leached, dark zones adjacent to the pegmatites can be seen in figs. 1, 9, 10, 13, 14, and 15. These zones were carefully examined in the field and are truly basified zones, not merely darker in appearance due to change of grain size; hornblende is enriched in these zones.

The plagioclase of the pegmatites is less basic than that of the surrounding amphibolite. Such is also the case for other small pegmatites in the Kongsberg—Bamble formation which the author has examined (REITAN, 15, 16) and, as was the case for these other pegmatites, this is most probably due to the diffusion rate of Na being more rapid than that of Ca. Because the pegmatites on Rytterholmen have been very locally derived, the differentiation of Na and Ca has not been very large and the difference between the plagioclase in the

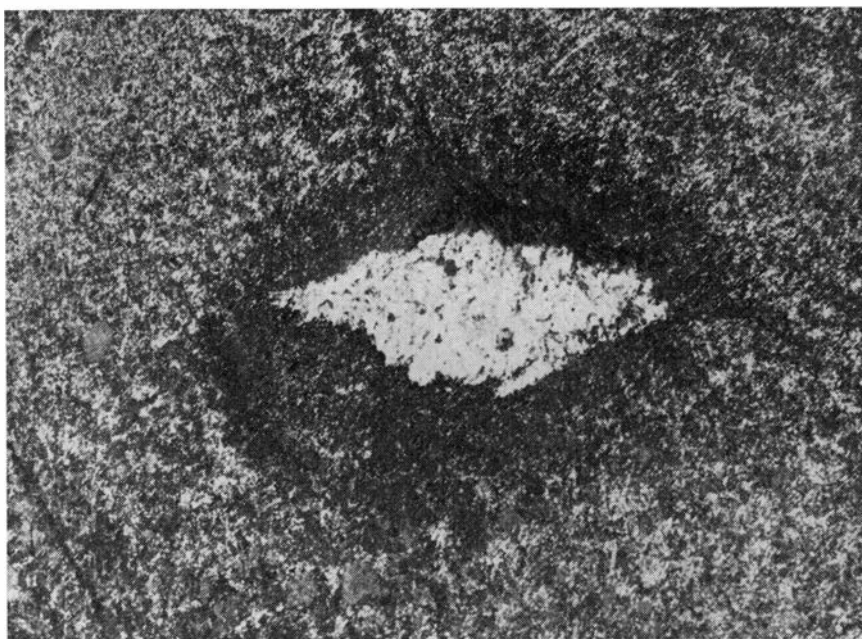


Fig. 13. Unusually strongly marked basified zone around a 20 cm long pegmatite in the amphibolite at area C. Photo by P. Reitan.

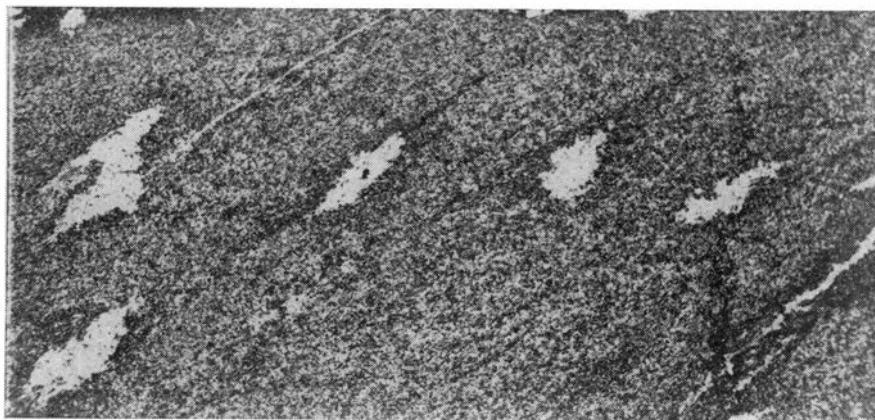


Fig. 14. Basified zones around pegmatites nearly parallel to the strike of the surrounding amphibolite at area E. The pegmatite with the central black spot is 13 cm long. Photo by P. Reitan.

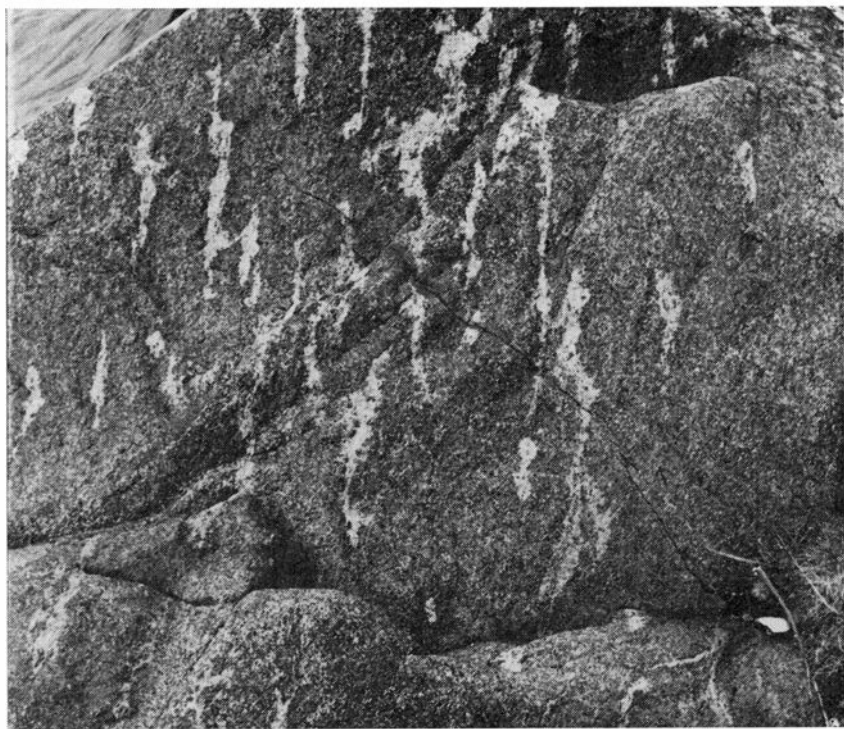


Fig. 15. Elongate pegmatites at area B. The photo shows about 3 m breadth at the bottom. The exposure is almost vertical; the pegmatites have the same shape on horizontal exposures. Photo by P. Reitan.

amphibolite (An_{42-44}) and in the pegmatites (An_{38-40}) is therefore not very large.

Areas B, C, and D are in structural positions completely comparable to that of A, the only differences being that area B is slightly closer to the apex of the fold and areas C and D are slightly farther away. This leads to small differences in the relative magnitude of the processes which tend to cause shear and tension.

The two oblique shear directions due to compression are probably best developed at distances farthest from the apices of the folds. Rotational shear is probably best developed at some point between the apex of the fold and the mid-point of the flank. The intensity of the shear couple due to movement along the boundaries between the

amphibolite and the quartzite will increase with distance from the apices of the folds. The shear across the flanks of the amphibolite layer due directly to the regional pressure on the folded competent layer surrounded by relatively plastic material is greatest about midway between the apices of the folds, assuming symmetrical folds in the layer. Tension due to stretching of the folded layer will be greatest at the apex of the fold and on the flanks at points farthest from the apices; due to plastic flow of the quartzite it will be greatest at points farthest removed from the apices of the folds. These factors, along with such things as the local composition of the amphibolite and inhomogeneities in the amphibolite, will combine to determine the number, size, shape, and attitude of the pegmatites.

Area E is in a somewhat different structural position, in that it is so close to the axis of the fold. Here the two oblique shear directions due to compression are minimal. Rotational shear is, though not absent, not intense. The shear couple due to movement along the boundaries of the band approaches its minimum. Shear across the amphibolite due directly to the regional pressure will not be very effective in the arch of a fold in a competent layer surrounded by relatively plastic material. The tension due to stretching will be great at the apex of the fold, will be perpendicular to the tangent to the arc of curvature, and will diminish with distance from the apex. However, in the axial region of the fold another form of shear will play a role of importance, namely concentric shear joints. This, combined with the tension perpendicular to the tangent to the arc of curvature of the fold, will yield zones nearly parallel to the strike in which there exist both the shear-stress on the mineral grains necessary to start recrystallization and a component of tension perpendicular to the direction of the shearing-stress. The result is that the pegmatites in this area will be oriented with their long axes more nearly parallel to the strike of the amphibolite than was the case along the flanks of the fold. Such was also observed to be the case (cf. figs. 6 and 14).

The lengths and the widths of the pegmatites in four of the areas were measured and the ratio of the length to the width calculated. The results of these measurements and calculations are:

Area	l/w max.	l/w min.	l/w average	Area	l/w max.	l/w min.	l/w average
A	10.0	1.4	4.3	C	6.3	1.7	3.4
B	14.0	3.7	7.6	E	6.7	1.5	3.0

After examining the other data which are available the best correlation seems to be with the amount of light minerals present or, inversely, with the sum of the dark minerals in the amphibolite. Otherwise stated the correlation is inverse to the basicity of the amphibolite. As it is well established that basic rocks are less plastic than more acidic rocks during metamorphism (see e.g. HOFSETH, 9, and RAMBERG, 13 and 14) this is then a positive correlation with the plasticity of the amphibolite. This is of course reasonable. The growth of the pegmatites in the amphibolite is a response to the deformation and will tend to relieve the stress which is their cause. A brittle host rock to the pegmatites will be relatively little capable of plastic deformation, such that the relief of the stress (in this case elongation by plastic flow in the direction of the tension) will tend to be concentrated at the sites of the pegmatites. They will grow relatively more in the direction of tension than their counterparts in a more plastic rock. The pegmatites in the more basic and therefore less plastic host rocks become wider in comparison to their length than those in the more plastic rocks, as the direction of the tension is perpendicular to the length of the pegmatite bodies; the average ratio l/w decreases as the basicity of the amphibolite increases. The observations show that the amphibolite is most basic at areas C and E and the ratio l/w is lowest in these areas, although inverted with respect to the basicity of the amphibolite. However, the average at area E is based on only 15 measurements and is probably the least reliable average. Area A is less basic and has a higher ratio l/w , and area B, at which the least basic amphibolite was found, has the highest ratio l/w .

The process which has been described here to explain the mode of origin of the pegmatites is one which is believed to have taken place during the dynamo-thermal metamorphism of the area, a reaction which was initiated by and which relieved the stress which was created by the deformation. This process is also dependent on elevated temperature; at low temperature the reactions would be too sluggish and relief of the stress would have to occur by some other means. Specifically, in this case it is not believed that there has occurred rupture of the amphibolite at the sites of the pegmatites. The zones were subjected to a shear-stress, but the increased activity induced by the stress in these zones was enough, with such high temperature, to allow the stress to be relieved by a process of recrystallization and metamorphic differentiation before rupture occurred; the growth of

new crystals at the sites of the pegmatites kept up completely with the extension of the rock due to tension perpendicular to the shear-stress. To some extent the stress was also relieved by plastic deformation (through recrystallization) of the amphibolite.

The petrographic descriptions of the amphibolite indicate that this area has been subjected to only very insignificant retrograde metamorphism. It is therefore believed that, as there are no visible sheared zones associated with these pegmatites, zones of mechanically ruptured crystals did not exist at the time when the pegmatites were formed. Metamorphic recrystallization relieved the stress which could cause rupture before rupture occurred.

Acknowledgements

Thanks are due to Dr. H. Bjørlykke for permission to publish the paper, for allowing me to engage in this study while in the employ of the Geological Survey of Norway, and for allowing me the use of the facilities of the Geological Survey. The members of the staff of the Geological Survey of Norway have always been willing to give their valuable assistance. I wish also to express my sincere appreciation to Prof. T. F. W. Barth for making available the facilities of the Mineralogisk—Geologisk Museum, University of Oslo and for making himself available for discussion of these problems whenever I desired.

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Manuscript received March 20, 1959.

Printed September 1959